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Title: "Testing Advanced Computational Tools for 3D Seismic Analysis Using the SEG/EAGE Model Dataset"

Participants: Advanced Data Solutions, Amoco, Anadarko, ARCO, BHP Petroleum, BP, Burlington Resources, Chevron, Conoco, Edison Chouest Offshore, Exxon, GECO-Prakla, Golden Geophysical, Marathon, Mitchell Energy, Mobil, Paradigm Geophysical, PGS-Tensor, Phillips, Shell, Silicon Graphics/Cray, Texaco, Union Pacific Resources, Unocal, Western Geophysical, Lawrence Livermore, Los Alamos, Oak Ridge, Rice Univ./HARC, Stanford Univ./SEP, Univ. Calif./Davis, Univ. of Houston, SEG.

Statement of Problem: 3-D seismic surveys are being used to find, develop, and produce U.S. hydrocarbon resources from geological settings, such as beneath salt, that are increasingly complex, and difficult to image seismically. 3-D surveys have provided tremendous benefits, but have also produced major challenges for seismic processing and imaging. The high accuracy and resolution needed from the resulting images and the huge volume of input data are major factors driving advances in imaging. In addition, time-lapse (4-D) and multi-component (3- and 4-C) surveys have shown great potential but further add to the complexities of imaging and interpretation and to the volume of data to be processed. This project focuses on developing and testing new techniques to make 3-D seismic imaging and modeling better and faster. It is a collaborative industry-national laboratory-university project and consists of four related but separate tasks, which are unified by their use of the SEG/EAGE salt model and the acoustic numerical model data set (ANM) calculated from it. The salt model provides a complex geological setting and difficult imaging targets. Since the correct seismic image is known, deficiencies in images can be readily identified. Each task aims to solve a key problem in seismic imaging, modeling, and data analysis, and each has its own set of partners and industry liaison. The industry liaison provides technical leadership and guidance for the task, and facilitates the exchange of ideas and results. This proposal seeks funding for a broadly aimed project, with many participants. The overall goals of the project are to demonstrate the usefulness of the SEG/EAGE numerical model data, and help make the data set more accessible to researchers in industry. More specific goals are listed below for each task. Some would be completed with funding requested for this year; others are new initiatives that should provide significant results from the funding requested for this year, but which may need additional funding to reach fruition or may lead to a separate proposal next year.

Tasks and Contributions:

Task 1: Advanced Cost-Effective Imaging Techniques. The goal of this task is to develop and demonstrate 3-D imaging methods that are substantially faster than available methods, but which still produce high-fidelity images. One of these methods is a new procedure for 3-D prestack depth migration, termed "common-azimuth" imaging, which consists of two steps. First, a partial prestack-migration operator, Azimuth Moveout (AMO), transforms the original data set into one in which all source-receiver offsets are aligned along one common direction. The transformed traces are partially stacked by common offsets, then migrated using common-azimuth 3-D prestack depth migration. This technique speeds up imaging in proportion to the number of traces summed in the partial stack. It has worked well with the SEG/EAGE salt model data, and with a field data set from the North Sea. Since it is based on an approximation to the exact downward-propagation operator, the goal of this year's effort is to eliminate that approximation and generalize the method to "narrow-azimuth" imaging. The narrow-azimuth imaging method should retain the computational efficiency of common-azimuth imaging, yet it should be more accurate in the presence of complex velocity functions. Successful implementation of the narrow-azimuth imaging method would provide an efficient wave equation based alternative to Kirchhoff imaging methods, and may enable development of wave-equation based reflection tomography methods. Researchers at Stanford University and Los Alamos will do this work. The industry liaison is Charles C. Burch, Conoco.

Task 2: Elastic Numerical Modeling. Increased recent interest in multi-component (3-C and 4-C) data collection underscores the importance of understanding elastic wave propagation. Shear waves can have a substantial effect on images, since the imaging itself usually assumes only acoustic wave propagation. In addition to misimaging converted wave arrivals, trace amplitudes can be wrong because of wave conversions. Understanding how elastic waves propagate in complicated structures will require elastic wave modeling with realistic structural models. Computational requirements for elastic model calculations may be 100 to 200 times greater than for an equivalent acoustic problem. The goals of this work are to define realistic elastic model parameters and to compute 3-D elastic numerical data from the SEG/EAGE salt model using a numerical modeling code developed by this project. This work will be done by researchers at Los Alamos, Lawrence Livermore, Rice Univ./HARC, and Stanford Univ. The industry liaison is Fred Aminzadeh, Unocal.

Task 3: Physical Modeling. A physical model of the SEG/EAGE salt structure was used to collect two data sets using a simulation of a conventional marine survey and of a survey using receivers arranged to simulate vertical cables of receivers tethered to the sea floor. These data sets were collected to compare 3-D imaging results from the two very

different acquisition methods, as well as from the acoustic numerical data set. Data collected using vertical receiver cables are truly 3-D, since they cover a large range of azimuths. The existing physical model of the SEG/EAGE salt structure was built with materials that do not support shear wave propagation. Materials are available that do support shear wave propagation. We will investigate if it is feasible to construct a new model that supports shear waves and collect physical model data to augment and compare to the elastic model data. Researchers at Los Alamos and the University of Houston/AGL are doing this work. The industry liaison is Robert Wiley, Marathon.

Task 4: Unconventional Seismic Processing, Analysis and Inversion. This task is developing methods for faster and more reliable 3-D velocity estimation, and for solving inverse and rock property estimation problems. Building a reliable 3-D velocity model is an essential part of 3-D imaging, yet manual picking and tracking of seismic events in a 3-D volume is time consuming and error-prone, even for an experienced interpreter. A successful neural network technique for 2-D event picking and tracking is being extended to work with 3-D data. Event picking and tracking with a prestack 2-D data set is a 3-D problem, with the addition of the source-receiver offset. Working with a prestack 3-D seismic data set is a 5- or 6-D problem, since it adds two source-receiver offsets, and, depending on the design of the acquisition might add source-receiver azimuth. The automated methods being developed take advantage of the concepts of deformable contours and “snakes” from the field of computer vision research to carry the analysis through the 5- or 6-D data space. Development of new methods for solving large inverse problems and for seismic data synthesis and data fusion has been applied to problems of determining residual statics and estimating and extrapolating rock properties from seismic data. The methods provide excellent or optimal solutions, yet the problems can be so large, and the solution methods so complex, that physical intuition alone is not a reliable guide to estimating the uncertainty in the solutions. Determining the uncertainty in the solutions can be almost as important as the obtaining the solution itself. Thus, this work aims to develop a unique and robust methodology for uncertainty analysis. This work seeks to: 1) determine the confidence limits of the computed solution, and 2) provide a way to consistently combine field measurements with the computed solution to reduce the uncertainty in the solution. Work on this task will be done by researchers from Oak Ridge, Lawrence Livermore and the Univ. of California at Davis. The industry liaison is James Robinson, Shell.

Deliverables:

Task 1: Advanced Cost-Effective Imaging Techniques. The theory of narrow-azimuth imaging will be developed and implemented, and testing started. It would be tested with the SEG/EAGE salt model data. Imaging results will be compared with those from the common-azimuth imaging method to demonstrate the higher accuracy of narrow azimuth imaging and evaluate its computational cost compared to common-azimuth imaging and more conventional imaging.

Task 2: Elastic Numerical Modeling. Elastic parameters for the SEG/EAGE salt model will be refined to better represent the rock properties of realistic salt settings. The elastic modeling computer program E3D will be improved to incorporate some additional computational enhancements. E3D will be used to carry out a limited number of high frequency (15 Hz or higher) elastic simulations from the SEG/EAGE salt model.

Task 3: Physical Modeling. Additional data will be collected using the vertical receiver cable acquisition to fill in the deficiencies found from imaging of the initial data set. Additional portions of both the vertical receiver cable data set and the marine style data set will be imaged to further compare the two approaches to data acquisition. If it is feasible, data will be collected from a new physical model that supports elastic wave propagation.

Task 4: Unconventional Seismic Processing, Analysis and Inversion. The 3-D implementation of the neural network event picking and tracking will be refined and further evaluated. A paper in preparation for Geophysics will be completed. The uncertainty estimation work will develop the methodology of predicting uncertainty in complex nonlinear systems. The methodology will be demonstrated using the *NewNet* code for seismic data fusion and the *TRUST* algorithm, both of which were developed in earlier years of this project. A paper in preparation for Geophysics will be completed on the application of the *TRUST* algorithm to the problem of determining residual statics.

Funding Table:

	FY98 (Last Year)	FY99 (This Year)	FY00 (Next year)
Los Alamos National Laboratory	\$ 245K	\$ 415K	\$ 400K
Lawrence Livermore National Laboratory	\$ 190K	\$ 335K	\$ 400K
Oak Ridge National Laboratory	\$ 150K	\$ 150K	\$ 0K
Total DOE	\$ 585K	\$ 900K	\$ 800K
Industry Contributions:	\$ 700K	\$ 950K	\$ 850K
Contracts to universities: (included in DOE)	\$ 215K	\$ 280K	\$ 150K

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Accomplishments:

Task 1: Advanced Cost-Effective Imaging Techniques. The two components of common-azimuth prestack depth imaging, AMO and common azimuth migration, have been tested on the acoustic numerical data set from the SEG/EAGE salt model and a real data set. Results were as favorable as initially hoped. Tests of the AMO component on the numerical data showed that AMO is an efficient and accurate method for transforming 3-D prestack marine data. Testing of the full common-azimuth imaging procedure on the numerical data are still being completed. Testing of the full procedure with a real data set showed that common-azimuth imaging is an effective method for 3-D prestack depth imaging of marine data sets. The other part of this task was to investigate the use of 2-pass prestack depth imaging with the acoustic numerical data from the SEG/EAGE salt model. The 2-pass method requires significantly less computing resources than full imaging methods. In a simple geologic setting, the 2-pass method can provide a faster, yet reliable 3-D prestack migrated image. This task aimed to evaluate results from the 2-pass method from a more complex geological setting. The 2-pass procedure consists of a cross-line prestack time migration followed by an inline 2-D prestack depth migration. The 2-pass procedure is an approximation to a full 3-D prestack depth migration, and, as a result, can produce less accurate results from data in which there are significant lateral variation of velocities (such as the salt model). Results confirmed that the 2-pass method can image both top and bottom of salt effectively, and thus, can be a fast way to get an initial model and image down to the base of salt. As was expected, the 2-pass method was not as effective for imaging reflectors below salt.

Task 2: Elastic Numerical Modeling. Acoustic and elastic numerical model data were generated with the 3-D finite-difference wave propagation code, E3D. These data were from a single shot, multi-receiver (40,000 receivers) gather, with both acoustic and elastic simulations. The acoustic simulation used the acoustic velocity structure of the SEG/EAGE salt model, and the elastic simulation used elastic parameters derived from the acoustic velocity structure. The simulations required several hours of a 40 node Meiko CS-2 massively parallel supercomputer. To save computing time, the simulations used a source wavelet with 5 Hz central frequency. Although that frequency is too low to fully demonstrate the differences between acoustic and elastic wave effects, the data show significant differences. The E3D code has been provided to researchers at Phillips and is about to be released to the public domain. The Phillips researchers are using E3D to calculate elastic numerical data from exploration targets in the Gulf of Mexico. They are also providing ideas and suggestions to improve E3D. A paper summarizing the computing requirements for the computations and comparing the elastic and acoustic data is in preparation.

Task 3: Physical Modeling. Part of the vertical cable data set has been processed and imaged through prestack depth migration. Since the receivers are located well below the water surface, they record two distinct wavefields. An upgoing wavefield is comparable to what is usually recorded by a receiver near the surface. A downgoing wavefield results from reflection by the water surface. The two wavefields were imaged separately and then combined. The upgoing wavefield image provides better imaging of steeply dipping features, while the downgoing wavefield image contains longer offsets and should provide better imaging below salt. The combined image defines the top and base of salt fairly well, but does not do as well at imaging reflectors below the salt. This is believed to be a result of the data acquisition geometry, and collection of data with longer source-receiver offsets is being considered to improve imaging below salt.

Task 4: Unconventional Seismic Processing, Analysis and Inversion. A preliminary 3-D implementation of the neural network for event picking and tracking was developed and provided to Shell (and is available to other interested participants). Shell researchers adapted the 2-D implementation that was developed last year to their in-house processing package and achieved a 16-fold reduction in the time to complete a 2-D velocity analysis compared to manual picking. Shell researchers had estimated that a successful 3-D implementation of the automated picking algorithm could result in a 12-fold reduction in time to complete a 3-D velocity analysis compared to manual picking. Results from the 2-D implementation confirm the estimates of 3-D performance. Other work of this task involved developing and refining a global optimization technique, termed *TRUST* (Terminal Repeller Unconstrained Subenergy Tunneling). *TRUST* is guaranteed to find the global minimum of a relation and was applied to the problem of determining residual statics. This year *TRUST* received an R&D 100 award. These prestigious awards are given yearly by R&D Magazine in recognition of the most outstanding technology developments with commercial potential. In addition, an ultrafast neural network learning code for seismic data fusion, called *NewNet*, was developed. *NewNet* can be used as a general-purpose computational tool, and it can be trained in a single iteration. One application of *NewNet* is to predict pseudo well logs from seismic reflection data.

Results of project work have been reported in 38 publications. Four are peer-reviewed papers, four are trade-journal publications, and 30 are talks at professional meetings. The project is supporting research by several graduate students. One would complete his Ph.D. thesis with next year's funding. Results from this project were essential components of three workshops at professional society meetings (SEG and EAGE).